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Negating the Fulcrum Effect in Manual Laparoscopic Surgery: Investigating Skill Acquisition with a Haptic Simulator

Adam J. Spiers¹, Sarah Baillie², Tony G. Pipe³ and George Asimakopoulous⁴

I. ABSTRACT

Background – Manual laparoscopic surgery requires extensive training and familiarization. It has been suggested that motion inversion caused by the ‘fulcrum effect’ is key to motor challenges. We investigate the potential of a conceptual semi-robotic handheld tool that negates natural inversion.

Methods – A custom laparoscopic simulator with haptic feedback was developed to allow interactive evaluation of the conceptual tool via virtual prototyping, prior to fabricating a physical prototype.

Two groups of eight participants each used either the conceptual or a regular virtual tool over a ten week study to complete two abstract tasks of motor control and force regulation.

Results – Statistically significant higher rates of skill improvement were demonstrated with the conceptual tool for motion efficiency, task completion time and error reduction. Force regulation increased for both groups but without significant differences.

Conclusions – The results indicate potential for fulcrum-negating hand tools in reducing motor skill acquisition time.

Keywords – Laparoscopy, Minimally Invasive Surgery, Simulation, Training, Robot Design, Haptics, Human-Machine Interfaces, Virtual Reality, Fulcrum Effect

II. INTRODUCTION

Manual laparoscopic surgery, also known as minimally invasive surgery (MIS), has many benefits to patients. Incisions are smaller than conventional surgery, leading to reductions in risk of infection, blood loss, recovery times and cosmetic scarring [1]–[3]. Unfortunately, these benefits are offset by technical difficulties posed to surgeons in terms of limited visibility, reduced dexterity, movement challenges, distorted haptic perception, spatial incompatibility and increased cognitive loading [1][2][4]–[9]. The popular *da Vinci surgical system* has alleviated many issues of laparoscopy, by physically decoupling the surgeon and tool via a robotic, tele-operated master / slave interface [3][10]. However, the system has yet to find widespread acceptance in all aspects of surgery [11]. Additionally, the significant cost and space requirements of such a system can be prohibitive to some hospitals [12].

One particular difficulty that MIS surgeons contend with is the ‘fulcrum effect’ [1][13]–[15], which arises from the insertion of long and rigid tools into the body, via fixed ports in the abdominal wall. In this arrangement, lateral motions of the tool handle are scaled and inverted at the tool tip (Figure 1.a). It has been argued that such inversion creates significant motor control challenges [16], movement constraints [9], [17] and perceptual distortions [1][2][4], leading to subsequent hurdles to skill acquisition for trainee surgeons [3][11][13][14][17]–[22]. As such, training a junior surgeon for laparoscopic proficiency can be costly in terms of time, resources and patient safety [2], [3][23][24]. Great efforts have aimed to reduce training time in novice surgeons while also improving skill in experts [1]. This has led in part to the use of virtual reality trainers [19] and specialist tools to help alleviate dexterity limitations via articulated wrists [8][25] similar to those in *da Vinci EndoWrist* tools.

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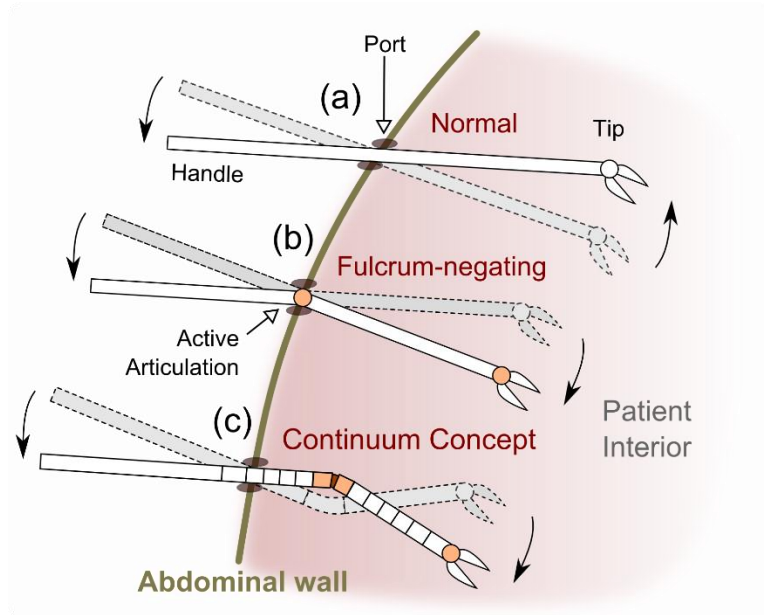


Figure 1: (a) Inversion associated with typical manual laparoscopic tools forms a barrier to skill acquisition. (b) Theoretically, this inversion may be negated via active counter-motion at the fulcrum. (c) A continuum structure allows a mechanically feasible moving point of articulation.

A. Inverting Tool Concept

An alternative solution to reducing MIS difficulty may be to negate the fulcrum effect locally, via counter-inversion of novel laparoscopic instruments during surgery. Such tools would actively articulate in response to handle motion in order to ‘cancel-out’ the normally inverted lateral tip motion. This effect could potentially bypass a major hurdle to laparoscopic skill acquisition, while maintaining other beneficial characteristics of manual MIS, such as surgeon proximity to the patient and other staff (in RMIS, the surgeon’s console is typically some meters away)

Of course, to achieve such tool articulation while retaining rigidity is mechanically non-trivial. In addition to lateral motions, laparoscopic instruments may also be moved in-line with the trocar (pushing into and pulling out of the body). This moves the location of the fulcrum along the tool shaft, meaning the point of articulation must also be moved (Figure 1.b). A similar effect may be mechanically achieved via a device with a number of articulation points, creating a continuum system (Figure 1.c). A conceptual illustration of how such a tool may be physically realized is provided in Figure 2, with a bank of actuators in the handle articulating the multi-segment tool shaft. Such a tool would be complex to fabricate, but less so than the many elements of the da Vinci Surgical System. Furthermore, though MIS provides hard constraints on tool dimensions and materials [26], projects such as ARAKNES have shown the feasibility of 12 DOF robotic manipulators that may be deployed via a single 30-35mm port [27]. Though ports do displace due to tissue compliance this should not affect the inverting tool more than a conventional tool, via gross translation.

Prior to constructing a prototype of the proposed tool, this study aims to evaluate the potential benefits of the system via the use of *virtual prototyping* (i.e. testing a system without having to physically build it). To achieve this goal we employ a custom laparoscopic simulator, in which the motion and environmental interactions of tools beyond the trocar may be simulated, while human user performance can be measured and compared across controlled scenarios.

B. Study Objectives

The goal of this study was to investigate whether inversion of laparoscopic tools could improve the acquisition of skills for trainee surgeons. This was achieved by evaluating skill in novice users (i.e. those with no prior surgical or MIS experience) of normal and inverting virtual laparoscopic tools over several weeks. Note that conducting this study with experienced surgeons would introduce a bias towards conventional tools, with which they are already expert users. Our approach made use of a physical tool handle connected to a commercial haptic interface, separated by a ‘trocar’. As in conventional MIS, all elements beyond the trocar (i.e. inside the patient) are displayed on a monitor.

C. Related Work

Different visuospatial skills [28] and cognitive remapping [11][18] are required to deal with the visual and proprioceptive discordance [13] of MIS. Perceptual limitations alone have been attributed to the high number of errors

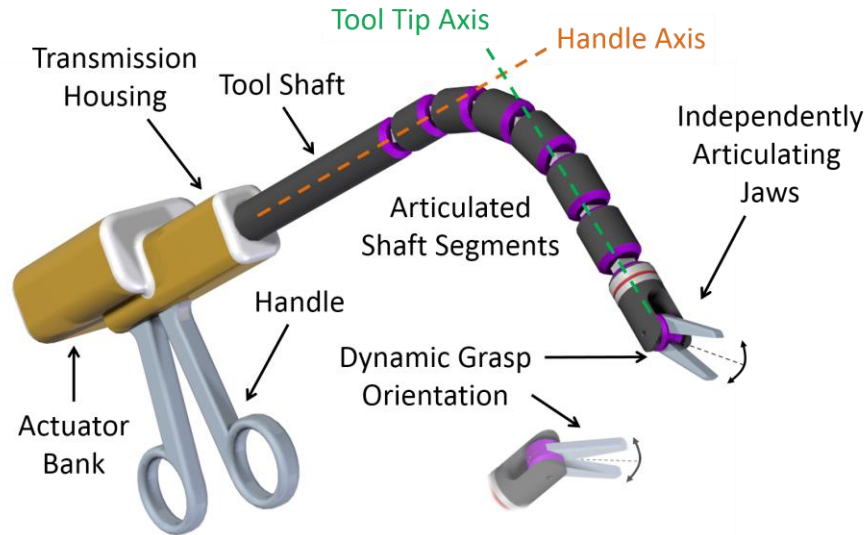


Figure 2: Conceptual illustration of an inverting tool. The independently articulating jaws enable the grasper to be independently orientated relative to the tool tip axis.

in laparoscopic versus open procedures [4][6][13]. We now examine work that has influenced this study and simulation system.

1) Impact of the Fulcrum Effect

Attempts to quantify the impact of the fulcrum effect on MIS performance were achieved via visual inversion about one lateral axis [13][14], leading to better novice performance. Though [13] determined visual inversion to be initially detrimental to experienced laparoscopic surgeons, this was rapidly overcome. Randomly alternating visual inversion in training tasks led to faster adaptation to the fulcrum effect [15]. Though visual inversion is a simple solution to aiding training, there are obvious limitations. For example, in standard bilateral tool use visual inversion will cause the right tool handle to control the left tool tip. In [18], mechanical forceps with constrained motion determined that the fulcrum effect increased task completion times.

2) Surgical Simulators

Virtual reality (VR) simulators are highly popular for laparoscopic training [16], offering risk free opportunities for developing transferrable MIS motor skills [30][31]. Virtual environments have been used to study the fulcrum effect, with inverting one-dimensional tools [17][32]. In [20], isolated kinematics determined that position rather than orientation control is most important for skill transfer. A simplified virtual environment allowed the study to focus on human skill acquisition.

3) Importance of Haptic Feedback in MIS training

A potential issue with commercial VR simulators is the lack of haptic feedback [19]. Despite haptics being distorted in manual MIS (due to tool length, inversion and trocar seals [1][4][5][14][29]) further haptic reductions have been linked to impaired surgical performance [4][6][16]. Huang et al. claim that haptics is 'essential for laparoscopic manipulation' [20]. The inclusion of haptics has been found to improve tasks such as knot-tying [10] and tissue identification [29]. Basdogan et al. argue that reduced haptic sensations are a reason for the extended training required for MIS [33]. Numerous groups have been motivated to incorporate haptic feedback into robotic tele-operators [10][34]. Physical 'box trainers' have been used alongside VR simulators to show that haptics reduces learning curves [7] and counters cognitive loading [2]. Experienced surgeons were shown to take most advantage of haptic feedback [2].

Due to the above factors, haptic feedback was included in this study, to facilitate realistic learning and performance.

4) Virtual Prototyping

As previously described, the use of virtual prototyping can alleviate the burden of constructing complex prototypes for conceptual device testing. Instead, users can interact with some physical aspects of a system while conceptual aspects are simulated. In [11], physical tool handles controlled virtual 'robotic instruments' for evaluation of different control modes, leading to optimized physical prototypes. Handle ergonomics for various virtual tools were considered in [35]. In [1], a laparoscopic tool connected to a haptic device allowed dynamic modification of virtual tool length and elastic constraints, as part of an investigation on stiffness perception.

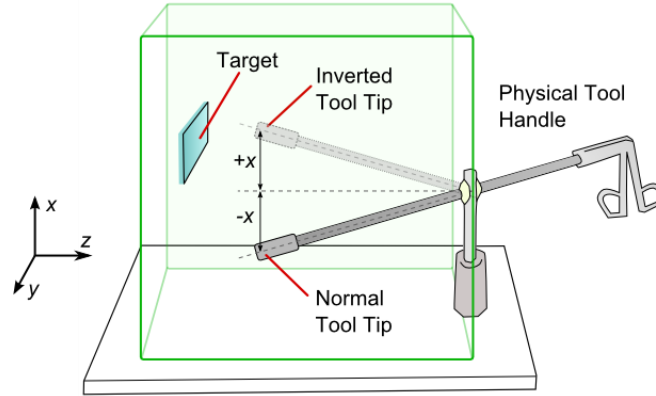


Figure 3: The virtual environment of the simulator. Normal or inverted (in x and y) tools may be simulated.

III. MATERIALS AND METHODS

A. Hardware components

The hardware aspects of the **custom** simulator include a physical laparoscopic tool handle attached to a rigid shaft, which passes through a trocar and is connected to a desktop haptic interface (Figure 3). By visually obscuring all elements of the physical simulator beyond the trocar, and displaying these elements on a nearby computer screen, an ‘endoscopic view’ of the ‘operating environment’ is created. This arrangement gives the user the sensation that they are controlling normal and inverting tools within a **physical** box trainer (Figure 4). The physical tool handle was taken from a steel laparoscopic grasper, whose original 4mm diameter shaft was substituted for a stiffer 10mm aluminum rod, to reduce oscillations during haptic interactions. A Novint FalconTM was used as the haptic interface due to its appealing robustness, stiffness, workspace dimensions and easily detachable end-effector. A custom, 3D printed tool interface was created for the Falcon, into which the rigid tool shaft was connected via an ‘Igus CL’ spherical bearing, (Figure 5). The shaft passed through a similar spherical bearing at the ‘trocar’ (Figure 5). Both bearings were abraded with a fine metal polish to reduce internal friction while maintaining low backlash. The inertia of the tool interface (without the modified tool) was compensated for in software.

The trocar and haptic interface were mounted on a rigid base with a separation of 0.15m between the trocar center and Falcon workspace center. A frame attached to the base supported a cloth cover, which visually obscured all elements beyond the trocar.

B. Software components

The virtual environment was created using the CHAI3D C++ library [36] and implemented on a laptop PC (Intel Core i5, 2.4GHz, 3GB RAM, Windows 7 32-bit).

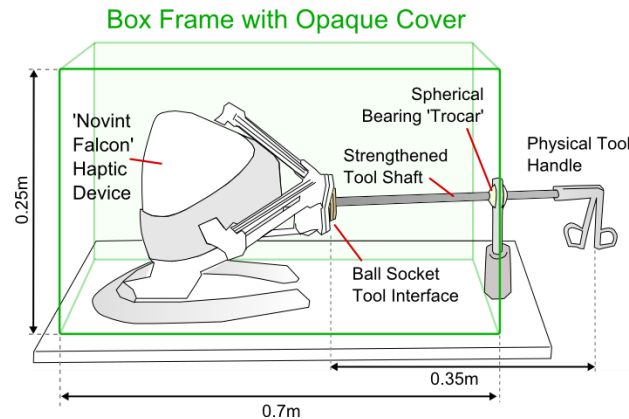


Figure 4: Hardware setup of the **custom** haptic laparoscopic simulator.



Figure 5: A spherical bearing mates the tool shaft with the haptic device via a custom 3D printed interface.

1) Tool Inversion

Core functions of CHAI3D were modified to **enable** tool tip motion inversion in x and y directions (Figure 4) with appropriate haptic effects. The common point-proxy rendering algorithm [37] was modified for the **inverted** scenario as follows:

$$F_d = \begin{bmatrix} -F_x \\ -F_y \\ F_z \end{bmatrix}, \quad F = Pp(p, \dot{p}_f), \quad \dot{p}_f = \begin{bmatrix} -\dot{x} \\ -\dot{y} \\ \dot{z} \end{bmatrix} \quad (1)$$

Where F_d is the force output to the haptic device, based on the force F , as generated by the point-proxy algorithm (Pp). Pp is a function of position p , and inverted velocity \dot{p}_f of the tool.

2) Haptic Rendering of the Tool Shaft

Typical haptic simulations utilize a spherical point cursor, referred to as the Haptic Interaction Point (HIP) and located at the tip of a graphically rendered tool [38]. Such ‘point probe’ haptic rendering greatly simplifies collision detection and other processes [38], compared to more realistic models and interactions. **However, constraining users to only point interactions limits ‘suspension of disbelief’ in some haptic simulators, particularly as the long and thin nature of laparoscopic tools lends themselves to object interactions along the tool shaft.** Benefits of non-point interaction in laparoscopic simulation are presented in [33], which implements *ray-based* rendering. As CHAI3D does not inherently support ray-based rendering, an alternative method was created.

In our method, several equally spaced HIPs are implemented along the length of the tool shaft, with the most distal being at the tool tip. HIP spacing is less than the width of virtual objects in the environment. The kinematic position of the tool tip HIP is controlled by the haptic device, with the position of all other HIPs calculated via spherical co-ordinate transformations **from the trocar**. Point-proxy calculations on all HIPs generate interaction forces, which are summed before being rendered on the haptic device. When the tool is inverted, equation (1) is applied to all HIPs.

A graphical 3D mesh model of a laparoscopic probe is anchored to the most distal HIP when the tool is not in contact with any objects. When a collision is detected, the tool mesh is anchored to the first colliding HIP’s virtual point proxy, with an appropriate offset (Figure 6). This method provides the visual and haptic sensations of collisions along the tool shaft. The graphical tool model is symmetrical about its length, so that rolling motion of the physical handle does not cause a discrepancy in tool appearance.

IV. EXPERIMENTAL METHODS

A number of performance measures have been proposed for laparoscopic skill evaluation. Early studies evaluated task completion time [18] and task errors [19]. However, [9] showed that motion efficiency continues to improve after competition time stabilizes, illustrating that time alone is not a conclusive measure of skill. Verified commercial systems include metrics of task completion time, task errors, path-length and smoothness of motion on tasks that range from realistic surgical procedures to abstract games [39][40][41]. In this study **we evaluate time, errors, motion efficiency**

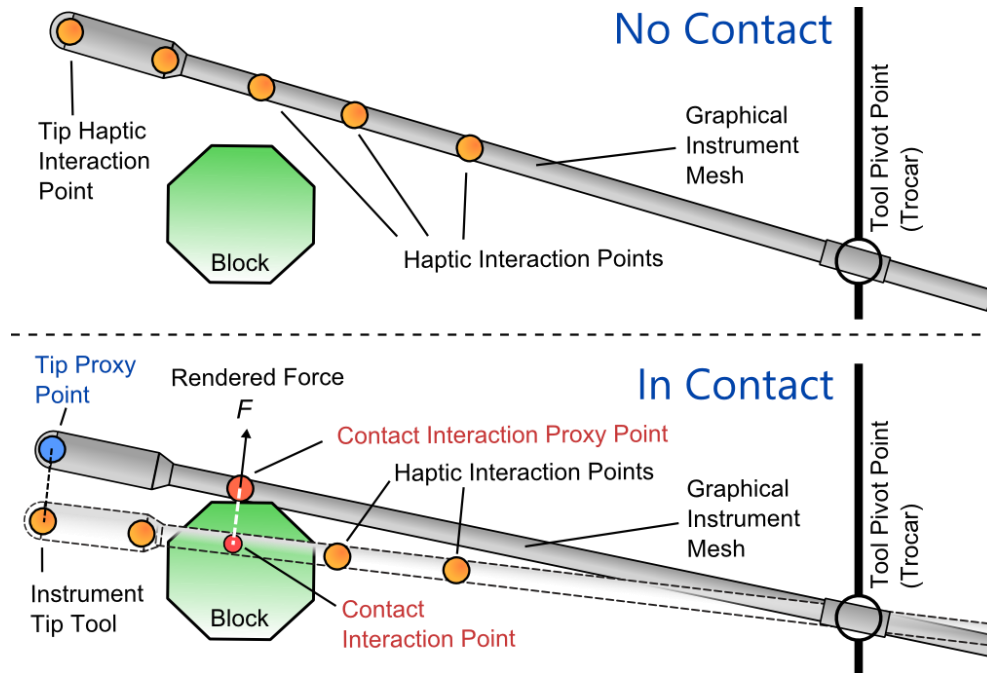


Figure 6: Haptic rendering of a instrument shaft interaction via the use of multiple independent haptic interaction points (HIPS). The graphical instrument mesh is dynamically anchored to different HIPS, enabling realistic visual behaviour.

and force using tasks chosen via discussions with laparoscopic surgeons at the UK-based Bristol Heart Institute and Bristol Urological Institute.

This study received ethical approval from the University of the West of England (UWE), reference number FETREC12-13/6, as confirmed on 16 June 2016 by the Chair of the Faculty Research Ethics Committee (FREC) of the Faculty of Environment and Technology (FET).

A. Task 1 – Reaching / Motion Efficiency

In the first task we study movement efficiency, based on the concept that tools that are easier and more intuitive to use lead to more efficient motion trajectories.

The task involved users touching a sequence of flat, vertically planar (i.e. in XY, Figure 4) and haptically stiff rectangular objects at various locations in the 3D workspace. Each rectangle changes color from green to blue when contacted by the tool tip (Figure 7a-b). When contact is released the object disappears and is replaced with a different size rectangle in a different XYZ location. Participants are instructed to move between objects efficiently (i.e. in a straight line) rather than quickly due to the ‘speed-accuracy tradeoff’ of Fitt’s law [42].

A. Task 2 – ‘Dissection’ / Motion and Force Control

The second task is loosely based on an arterial dissection task from laparoscopic cardiac surgery, where an artery must be gradually separated from adjacent tissue. Excessive movement or force in such a procedure will damage the tissue. In addition to motion inversion, the fulcrum effect also forms a lever arm that scales handle force into tip forces [1], adding further complications. Task 2 aims to study various aspects of tool control (completion time, motor control and force regulation) while completing a ‘surgical’ task.

In Task 2, participants use the virtual laparoscopic tools to push a series of seven connected blocks into a target region, defined by two horizontal boundary lines. The blocks begin above the boundary and are restricted to move only in the vertical (Y) plane. The blocks begin colored green and if pushed into the target area become blue. If they are pushed beyond the target area or with excessive force ($>4.5\text{N}$) they are considered ‘broken’. The blocks are displayed with empty space separating them, (Figure 8) to enable discrete visual display of each block’s color ‘state’.

The blocks are stiff haptic objects that have an octagonal structure (Figure 6) that enables good contact interaction with the virtual tool. The shape also reduces the distracting sensation of the haptic device ‘falling off the edge’ of cube-like objects. Once a block is ‘broken’ the tool is no longer able to push it or receive haptic feedback from it.

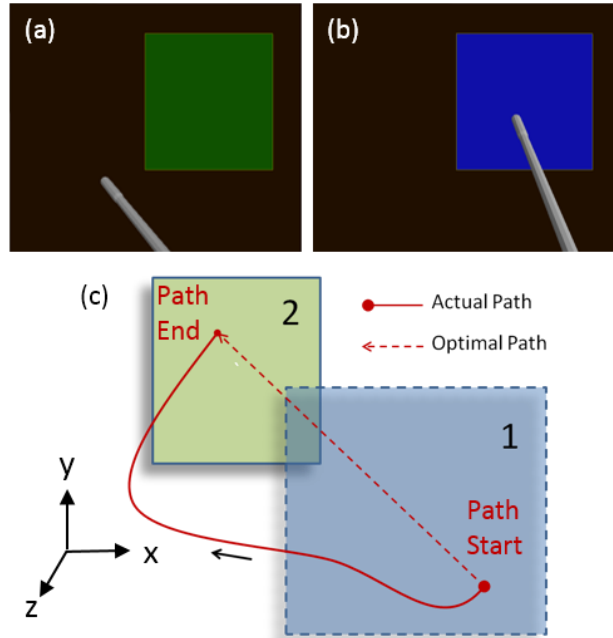


Figure 7: **Task 1**, the tool is used to touch sequential rectangular objects of various size and xyz location. a) simulation environment before touching the target object, b) when in contact c) **motion efficiency is evaluated using actual and optimal paths.**

As in [33], the blocks are connected together with virtual springs and dampers to form a continuous dynamic structure. If one block is pushed, transfer of forces through the dynamic elements will cause the rest of the structure to follow. Additionally, pushed blocks exert reaction forces and attempt to re-align with their neighbor when released. **The spring and damper coefficients, and ‘excessive’ force threshold were determined via pilot studies with a cardiac surgeon.**

Participants are requested to push all the blocks into the target area as quickly as possible while minimizing breakages. The task ends when all blocks are either in the target area (blue) or broken (red). To start each task the user pulls the tool handle out of the trocar as far as possible. The semi-conical workspace of the Falcon leads to a consistent starting position.

V. RESULTS

16 participants (2 female, ages 26-49, mean age = 31.9) took part in this study. No participants had color blindness issues (if they did, patterns would be used). The participants were members of a research laboratory with no prior surgical experience, so were not pre-conditioned to typical laparoscopic tools. 8 participants were randomly selected to use the ‘inverting’ tool, the remaining 8 participants used the normal tool. The study took part over three sessions, completed every four weeks. **In each session Task 1 was completed both before and after 10 repetitions of Task 2, with a 1 minute gap between tasks. This structure was designed to provide insight into both short (Task 1) and long term (Tasks 1 and 2) learning with the different tools.** Analysis of Covariance (ANCOVA) was used to evaluate whether the skill acquisition trends (over time) for each group were statistically different. Matlab’s *aoctool* command was used to consider overall improvement in a metric (mean average of measures per session, per participant) against the timing of the session (the predictor variable).

Some participants were unexpectedly unable to attend all three sessions. In the ‘inverted’ group, 2 individuals did not participate in session 3. In the ‘normal’ group 1 person did not attend session 2 while 3 people did not attend session 3. These changing participant quantities were considered in statistical analysis of the results. Overall there were 86 data points used in Task 1’s statistical analysis (1019 before taking means) and 60 data points (430 before taking means) for Task 2.

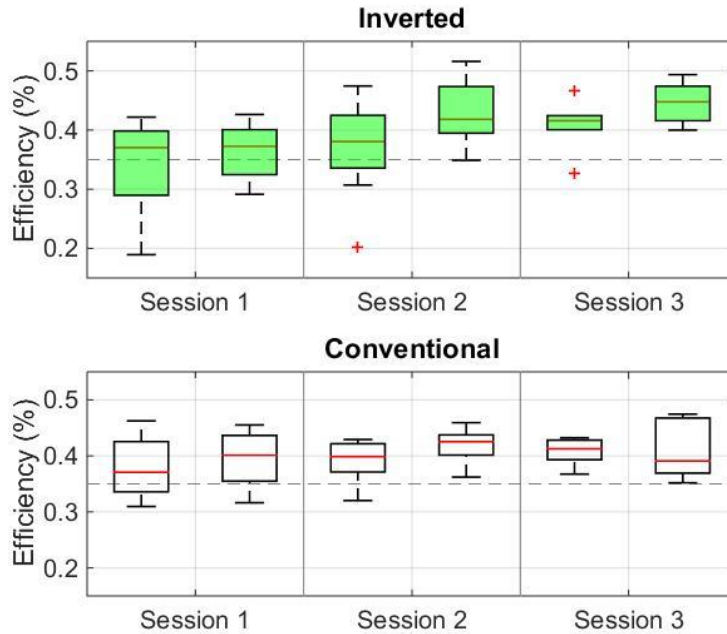


Figure 9: Box plot of motion efficiency across inverted and normal groups over the course of the Task 1 study. A took place at the start of the session (before Task 2). B took place afterwards.

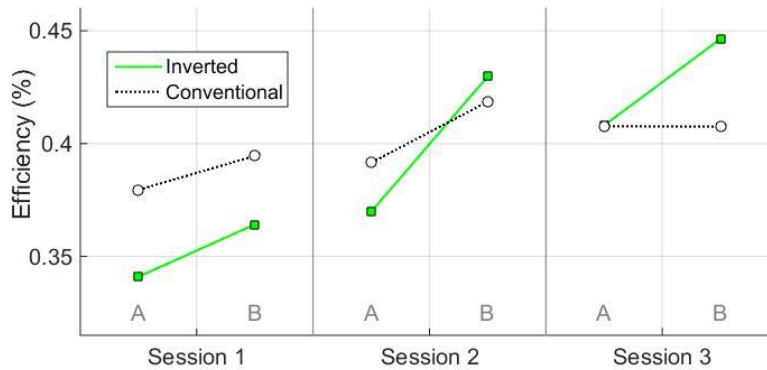


Figure 10: Mean group motion efficiency over the course of the study.

A. Task 1 Results

Motion efficiency during Task 1 is illustrated via box plots in Figure 9 and mean results in Figure 10. This was calculated as $Efficiency = Optimal\ Path\ Length / Actual\ Path\ Length$ (Figure 7).

The two groups begin the study with similar median scores, but a larger starting variance and lower mean efficiency in the inverted group. This may indicate some initial difficulty in learning to use the inverting tool, which does not behave like a typical lever. Both groups improve their performance between the start and end of each session as they become more proficient with the tools, though this is at a faster rate with the inverted tool. As the sessions progress a rise in overall efficiency is observed in both groups. Again, this is less pronounced for the conventional group, with no discernable improvement by Session 3.

ANCOVA analysis resulted in a statistically significantly ($p < 0.05$) rate of improvement for the inverted tool group ($F(1,85) = 6.56, p = 0.0105$) as reflected within each session and overall (Figures 9 and 10).

B. Task 2 Results

The block pushing task was evaluated via three metrics:

1. Task completion time
2. Number of blocks broken (errors)
3. Average force used throughout

The results are presented in Figures 11, 12 and 13 via boxplots and group mean results. These figures display absolute scores per session, in addition to overall improvement over the course of the study. Note that Task 1 was completed before and after Task 2 (as discussed above).

The mean time taken to complete the task is initially higher for the inverting tool, but decreases at a faster rate than the normal tool. Though participants improved in both cases, the rate of improvement and final time (at the end of the study) of the inverting group is superior to the conventional group. ANCOVA analysis illustrates that the rate of improvement was significantly better ($p < 0.05$) for the inverting group ($F(1,59) = 5.2, p = 0.0264$).

The number of blocks broken was also initially higher for the inverting tool, though this decreased in each trial. The blocks broken with the conventional tool increased slightly over the study. This coincides with the reduction in time taken, which implies lower motion accuracy (by Fitt's Law [42]). It appears that with the normal tool, time, force and motion accuracy are balanced in a trade-off, while this is not the case with the inverting tool. ANCOVA analysis indicated that the inverting group improved significantly better than the conventional group ($F(1,59) = 10.71, p = 0.0018$).

The average force increased over the course of the study for both groups, with a reduction in variance by the final sessions. ANCOVA indicated no significant differences between the groups ($F(1,59) = 3.64, p = 0.0615$).

Anecdotally, we suggest that the ability to regulate higher forces without increasing tissue damage is indicative of better tool control.

In summary, significantly higher rates of skill acquisition were demonstrated for the inverting tool group in terms of task completion time and error reduction. Both groups demonstrated equivalent improvement in force used.

VI. DISCUSSION

This paper has proposed that the inherent inversion of laparoscopic tools may be 'cancelled-out' via semi-robotic hand-held instruments with counteracting additional inversion. This could have beneficial impact on surgical skill acquisition and overall use. A virtual prototyping approach was used to create interactive models of ideal inverting and conventional tools which were then used for simulated experiments.

The higher rate of improvement of all measured metrics in this study indicated faster skill acquisition with an inverting tool. This is demonstrated both during each session (Task 1) in addition to over the course of weeks (Tasks 1 and 2). This study is, of course, greatly limited in terms of time commitment when compared to the training normally associated with learning a surgical skill.

As the simulations have been based on an 'ideal' fulcrum-negating tool, future work will seek to consider feasible mechanical solutions and factor in movement limitations, reconfiguration speed and grip orientation methods. If the simulated tool continues to be successful, a physical tool will be designed and fabricated for experimental validation.

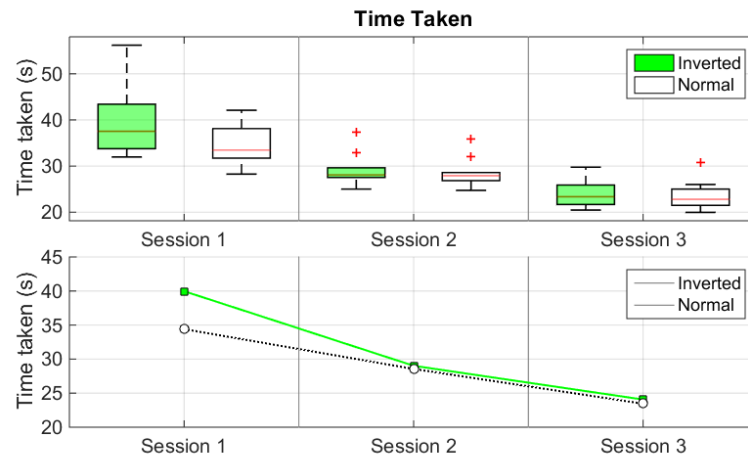


Figure 11: Time taken to complete Task 2. The bottom plot shows group mean results.

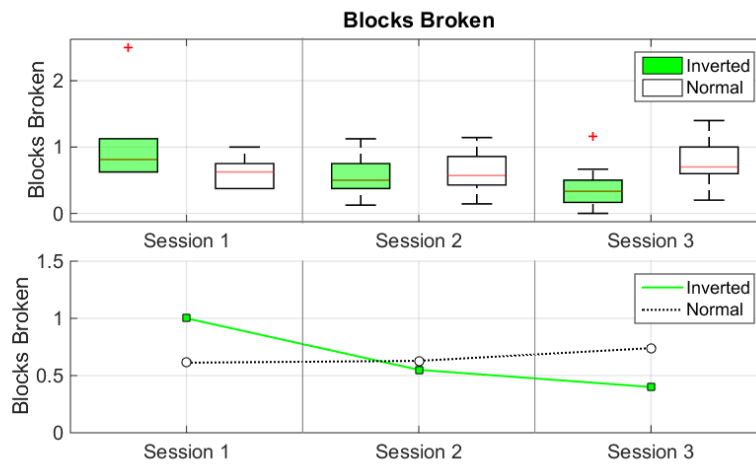


Figure 12: Blocks Broken during Task 2.

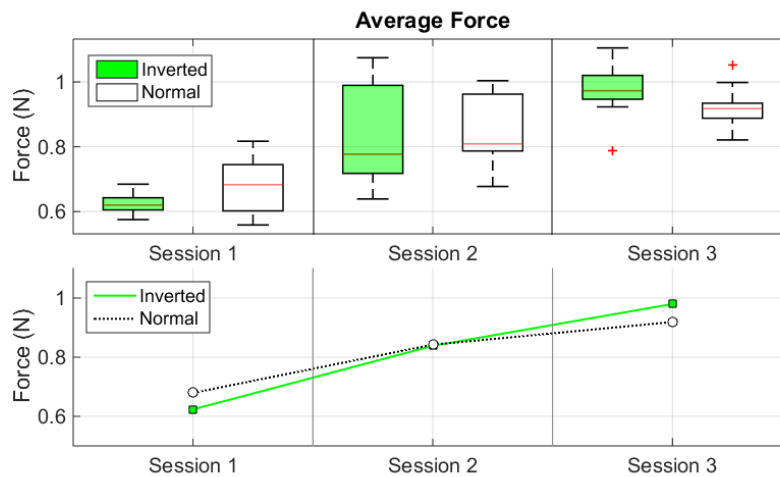


Figure 13: Average force applied to blocks via the tool, in Task 2.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to disclose with regard to this work.

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REFERENCES

- [1] I. Nisky, F. Huang, A. Milstein, C. M. Pugh, F. a Mussa-Ivaldi, and A. Karniel, "Perception of stiffness in laparoscopy - the fulcrum effect.," *Studies in health technology and informatics*, vol. 173, pp. 313–9, Jan. 2012.
- [2] C. G. L. Cao, M. Zhou, D. B. Jones, and S. D. Schwartzberg, "Can surgeons think and operate with haptics at the same time?," *Journal of gastrointestinal surgery : official journal of the Society for Surgery of the Alimentary Tract*, vol. 11, no. 11, pp. 1564–9, Nov. 2007.
- [3] A. Amodio, A. Linares Quevedo, J. V. Joseph, E. Belgrano, and H. R. H. Patel, "Robotic laparoscopic surgery: cost and training.," *Minerva urologica e nefrologica = The Italian journal of urology and nephrology*, vol. 61, no. 2, pp. 121–8, Jun. 2009.
- [4] D. Greenwald, C. G. L. Cao, and E. W. Bushnell, "Haptic Detection of Artificial Tumors by Hand and with a Tool in a MIS Environment," vol. 5, no. 2, pp. 131–138, 2012.
- [5] F. Bello, T. Coles, D. Gould, and C. Hughes, "The Need to Touch Medical Virtual Environments?," *IEEE Virtual Reality 2010 VR2010 Workshop on Medical Virtual Environments*, pp. 1–3, 2010.
- [6] H. Xin, J. Zelek, and H. Camahan, "Laparoscopic surgery, perceptual limitations and force: A review," *First Canadian Student Conference on Biomedical Computing*, vol. 144, 2006.
- [7] M. Zhou, S. Tse, a Derevianko, D. B. Jones, S. D. Schwartzberg, and C. G. L. Cao, "Effect of haptic feedback in laparoscopic surgery skill acquisition.," *Surgical endoscopy*, vol. 26, no. 4, pp. 1128–34, Apr. 2012.
- [8] N. Di Lorenzo, I. Camperchioli, and a L. Gaspari, "Radius surgical system and conventional laparoscopic instruments in abdominal surgery: application, learning curve and ergonomy.," *Surgical oncology*, vol. 16 Suppl 1, pp. S69-72, Dec. 2007.
- [9] C. D. Smith, T. M. Farrell, S. S. McNatt, and R. E. Metreveli, "Assessing laparoscopic manipulative skills.," *American journal of surgery*, vol. 181, no. 6, pp. 547–50, Jun. 2001.
- [10] A. Okamura, L. Verner, C. Reiley, and M. Mahvash, "Haptics for robot-assisted minimally invasive surgery," *Robotics research*, vol. 2, 2011.
- [11] A. Zahraee and J. Paik, "Toward the development of a hand-held surgical robot for laparoscopy," ... /*ASME Transactions on*, vol. 15, no. 6, pp. 853–861, 2010.
- [12] J. G. Bittner, C. A. Hathaway, and J. A. Brown, "Three Dimensional visualisation and articulating instrumentation: Impact on simulated laparoscopic tasks," *Journal of minimal access surgery*, vol. 4, no. 2, pp. 31–8, Apr. 2008.
- [13] Crothers I. R., A. G. Gallagher, N. McClure, D. T. D. James, and J. McGuigan, "Experienced laparoscopic surgeons are automated to the fulcrum effect : An ergonomic demonstration," *Endoscopy*, vol. 31, no. 5, pp. 365–369, 1999.
- [14] A. G. Gallagher, N. McClure, J. McGuigan, K. Ritchie, and N. P. Sheehy, "An ergonomic analysis of the fulcrum effect in the acquisition of endoscopic skills.," *Endoscopy*, vol. 30, no. 7, pp. 617–20, Sep. 1998.
- [15] J. A. Jordan, A. G. Gallagher, J. McGuigan, and N. McClure, "Randomly alternating image presentation during laparoscopic training leads to faster automation to the 'fulcrum effect'.," *Endoscopy*, vol. 32, no. 4, pp. 317–21, Apr. 2000.
- [16] T. R. Coles, D. Meglan, S. Member, and N. W. John, "The Role of Haptics in Medical Training Simulators : A Survey of the State of the Art," vol. 4, no. 1, pp. 51–66, 2011.
- [17] M. Janczyk, R. Pfister, and W. Kunde, "On the Persistence of Tool-Based Compatibility Effects," *Zeitschrift für Psychologie*, vol. 220, no. 1, pp. 16–22, Jan. 2012.
- [18] A. J. Hodgson, J. G. Person, S. E. Salcudean, and A. G. Nagy, "The effects of physical constraints in laparoscopic surgery.," *Medical image analysis*, vol. 3, no. 3, pp. 275–83, Sep. 1999.
- [19] A. K. Madan, C. T. Frantzides, N. Shervin, and C. L. Tebbit, "Assessment of individual hand performance in box trainers compared to virtual reality trainers.," *The American surgeon*, vol. 69, no. 12, pp. 1112–4, Dec-2003.
- [20] F. Huang, F. Mussa-Ivaldi, C. Pugh, and J. Patton, "Learning kinematic constraints in laparoscopic surgery," *Haptics, IEEE Transactions on*, vol. 5, no. 4, pp. 356–364, 2011.
- [21] J. A. Jordan, A. G. Gallagher, J. McGuigan, and N. McClure, "Virtual reality training leads to faster adaptation to the novel psychomotor restrictions encountered by laparoscopic surgeons.," *Surgical endoscopy*, vol. 15, no. 10, pp. 1080–4, Oct. 2001.
- [22] H. Heuer, F. Klimmer, A. Luttmann, and U. Bolbach, "Specificity of motor learning in simulator training of endoscopic-surgery skills.," *Ergonomics*, vol. 55, no. 10, pp. 1157–65, Jan. 2012.
- [23] M. Bridges and D. L. Diamond, "The financial impact of teaching surgical residents in the operating room.," *American journal of surgery*, vol. 177, no. 1, pp. 28–32, Jan. 1999.
- [24] A. J. Vickers, C. J. Savage, M. Hruza, I. Tuerk, P. Koenig, L. Martínez-Piñeiro, G. Janetschek, and B. Guillonneau, "The surgical learning curve for laparoscopic radical prostatectomy: a retrospective cohort study.," *The lancet oncology*, vol. 10, no. 5, pp. 475–80, May 2009.
- [25] F. Jehl, R. Pessers, and P. Breedveld, "DragonFlex – Smart Steerable Laparoscopic Instrument," *Journal of Medical Devices*, vol. 7, pp. 3–4, 2013.
- [26] A. J. Spiers, H. J. Thompson, and A. G. Pipe, "Investigating Remote Sensor Placement for Practical Haptic Sensing with EndoWrist Surgical Tools," 2015.
- [27] M. Piccigallo, U. Scarfogliero, C. Quaglia, G. Petroni, P. Valdastrì, A. Menciassi, and P. Dario, "Design of a Novel Bimanual Robotic System for Single-Port Laparoscopy," vol. 15, no. 6, pp. 871–878, 2010.

- [28] C. J. Lin and H.-J. Chen, "The Investigation of Laparoscopic Instrument Movement Control and Learning Effect," *BioMed Research International*, vol. 2013, pp. 1–16, 2013.
- [29] J. Perreault and C. Cao, "Effects of vision and friction on haptic perception," *Human Factors: The Journal of the ...*, 2006.
- [30] J. a Jordan, a G. Gallagher, J. McGuigan, and N. McClure, "Virtual reality training leads to faster adaptation to the novel psychomotor restrictions encountered by laparoscopic surgeons.," *Surgical endoscopy*, vol. 15, no. 10, pp. 1080–4, Oct-2001.
- [31] T. P. Grantcharov, V. B. Kristiansen, J. Bendix, L. Bardram, J. Rosenberg, and P. Funch-Jensen, "Randomized clinical trial of virtual reality simulation for laparoscopic skills training.," *The British journal of surgery*, vol. 91, no. 2, pp. 146–50, Feb. 2004.
- [32] W. Kunde, J. Müsseler, and H. Heuer, "Spatial Compatibility Effects With Tool Use," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 49, no. 4, pp. 661–670, Aug. 2007.
- [33] C. Basdogan, S. De, J. Kim, M. Muniyandi, H. Kim, and M. A. Srinivasan, "Haptics in Minimally Invasive Surgical Simulation," *Ieee Computer Graphics And Applications*, no. April, pp. 56–64, 2004.
- [34] E. B. Vander Poorten, E. Demeester, and P. Lammertse, "Haptic feedback for medical applications , a survey," in *Actuator*, 2012, pp. 1–6.
- [35] U. Matern, S. Konecny, M. Tedeus, K. Dietz, and G. Buess, "Ergonomic testing of two different types of handles via virtual reality simulation.," *Surgical endoscopy*, vol. 19, no. 8, pp. 1147–50, Aug. 2005.
- [36] F. Conti, F. Barbagli, D. Morris, and C. Sewell, "{CHAI} – An Open-Source Library for the Rapid Development of Haptic Scenes," 2005.
- [37] D. C. Ruspini, K. Kolarov, and O. Khatib, "The haptic display of complex graphical environments," *Proceedings of the 24th annual conference on Computer graphics and interactive techniques SIGGRAPH 97*, vol. vol, no. Annual Conference Series, pp. 345–352, 1997.
- [38] K. Salisbury, F. Conti, and F. Barbagli, "Haptic rendering: introductory concepts.," *IEEE computer graphics and applications*, vol. 24, no. 2, pp. 24–32, 2004.
- [39] T. P. Grantcharov, L. Bardram, P. Funch-Jensen, and J. Rosenberg, "Learning curves and impact of previous operative experience on performance on a virtual reality simulator to test laparoscopic surgical skills," *The American Journal of Surgery*, vol. 185, no. 2, pp. 146–149, Feb. 2003.
- [40] A. G. Gallagher, Ph.D., K. Richie, B.Sc., N. McClure, M.D., J. McGuigan, A. G. Gallagher, K. Richie, and N. McClure, "Objective Psychomotor Skills Assessment of Experienced, Junior, and Novice Laparoscopists with Virtual Reality," *World Journal of Surgery*, vol. 25, no. 11, pp. 1478–1483, Nov. 2001.
- [41] V. Chandra, D. Nehra, R. Parent, R. Woo, R. Reyes, T. Hernandez-Boussard, and S. Dutta, "A comparison of laparoscopic and robotic assisted suturing performance by experts and novices.," *Surgery*, vol. 147, no. 6, pp. 830–9, Jun. 2010.
- [42] P. M. Fitts and J. R. Peterson, "Information Capacity of Discrete Motor Responses," *Journal of experimental psychology*, vol. 67, no. 2, pp. 103–112, 1964.